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NUREG-1101
Vol. 2

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# Onsite Disposal of Radioactive Waste

## Methodology for the Radiological Assessment of Disposal by Subsurface Burial

**U.S. Nuclear Regulatory Commission**

Office of Nuclear Material Safety and Safeguards

S. M. Neuder and W. E. Kennedy, Jr.

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# Onsite Disposal of Radioactive Waste

## Methodology for the Radiological Assessment of Disposal by Subsurface Burial

Manuscript Completed: January 1987
Date Published: February 1987

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## ABSTRACT

Volume 1 of this NUREG provides guidance for academic, medical, and industrial licensees seeking authorization to dispose of small quantities of radioactive material by onsite subsurface disposal. Licensee requests for such authorizations are made pursuant to Section 20.302 of 10 CFR Part 20 "Standards for Protection Against Radiation." Volume 1 supplements Section 20.302 to assure that appropriate information is provided by the licensee and describes disposal methods and techniques acceptable to the NRC staff in its evaluation of the application.

In addition, Volume 1 identifies categories of radionuclides defined for subsurface disposal. Limiting conditions are described for each category of radionuclides with respect to total radioactivity, waste packaging, burial frequency and other conditions likely to be acceptable for subsurface disposal. The categories of radionuclides and associated disposal conditions and criteria are the primary data by which the NRC staff will make an initial evaluation of information provided in the application. Applications for proposed disposal activities that do not fit any of the disposal categories may need to be evaluated against more detailed guidance described in this volume (Volume 2).

This volume describes the criteria and technical methodology used by NRC staff to evaluate requests by licensees for approval of onsite disposal by burial in soil. The technical methodology includes the ONSITE/MAXI1 code for calculating radiological exposure from various pathways, the MOCMOD84 code, and analytical methods for calculating contaminant transport and concentration of radionuclides in flowing groundwater. Radiological exposure analyses include the following pathways: (1) exposure to direct gamma from any surface contamination or buried waste, (2) drinking water from a well contaminated by migration of radionuclides, (3) ingesting agricultural products derived from radionuclide-contaminated soil, and (4) inhaling radionuclides resuspended at the burial site. Licensee-proposed disposal activities are evaluated in terms of radiological impact on public health and safety and the environment. The estimated committed effective dose equivalent resulting from the technical evaluation will usually be the determining factor in the authorization of the proposed disposal.




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ACKNOWLEDGEMENT

The authors wish to acknowledge the valuable support of Mr. Robert E. Browning, Director, Division of Waste Management, Mr. Richard E. Cunningham, Director, Division of Fuel Cycle and Material Safety, and Mr. Vandy L. Miller, Chief, Material Licensing Branch, Division of Fuel Cycle and Material Safety, during the development and implementation of 10 CFR 30.302 disposal assessment methodology.

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# 1 INTRODUCTION

Pursuant to Section 20.302 of 10 CFR Part 20 [Code of Federal Regulations, Title 10, Part 20], any licensee or applicant for a license may apply to the U.S. Nuclear Regulatory Commission (NRC) for approval of proposed procedures to dispose of licensed or any other radioactive material in a manner not otherwise authorized in the regulations. Section 20.302 of the regulations provides the licensee with an alternative to the more conventional means of disposal of their radioactive waste. For example, the conventional disposal of a large volume of soil contaminated with trace quantities of radioactivity may require that several hundred drums be shipped to a commercial waste disposal site. In this situation, the licensee may wish to seek NRC authorization under §20.302 to bury the slightly contaminated radioactive soil in a trench located on the licensee's own property. Licensee proposals pursuant to §20.302 are reviewed by the NRC on a case-by-case basis and are assessed primarily in terms of potential radiological impacts on public health and safety. These impact assessments will strongly depend on the site-specific and other information provided by the licensee when submitting a request for disposal authorization.

The specific information required from the licensee and a description of disposal methods and techniques likely to be acceptable to the NRC staff in its evaluation of the application is described in Volume 1 of this NUREG [Neuder, 1986]. In addition, Volume 1 identifies three categories of radionuclides defined for subsurface disposal. Limiting conditions are described for each category of radionuclides with respect to total radioactivity, waste packaging, burial frequency, and other conditions acceptable for subsurface disposal.

The application process is simplified if the requested disposal activity falls within a given disposal category and the associated criteria, as described in Volume 1, can be met by the applicant. For proposed disposal activities which do not fall within any of the three categories, as for example unpackaged disposals or disposal quantities which exceed those specified, a more detailed application may be necessary and technical assessments of the types described in this document should be performed by the licensee.

Radiological impact assessments of licensee-proposed disposal activities include consideration of site-specific exposure pathways and exposure scenarios. In general, the critical exposure pathways include (1) external radiation exposure directly from contaminated surface soil and from buried waste, (2) internal exposure from resuspension and inhalation of airborne radionuclides, (3) internal exposure from ingestion of food crops and animal products derived from the site, (4) internal exposure from drinking contaminated water from a nearby well, and (5) internal exposure from drinking water from a well constructed within the waste disposal area itself. Dose rates to an individual located on or near the site are calculated from the quantity and concentration of radioactivity in the soil, water, and air medium near the disposal site and the individual's rate of exposure to the radiation from appropriate pathways.



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In general, the committed effective dose equivalent will be the primary factor in determining whether the licensee's proposed disposal activities will or will not be authorized. When authorized, burials by the licensee under prescribed conditions and restrictions on surrounding land use will provide reasonable assurance that the potential dose to an individual on or near the site will be within acceptable limits.

Section 20.302 of the regulations is applicable to all NRC licensees including industrial, medical, academic and reactor licensees. For example, a nuclear power reactor licensee may request authorization for onsite burial of equipment or materials which has become slightly contaminated during routine reactor operations. Although differences exist between power reactor sites and sites of other types of facilities, radiological impact assessments of reactor waste disposals pursuant to §20.302 proceed along the same lines as those described in this document.

Disposal of radioactive waste by burial on the licensee's property or by other means, pursuant to §20.302, and the methodology for the radiological impact assessments of these types of disposal activities are the subjects of this volume (Volume 2 of this NUREG series).

Volume 3 of this NUREG series [Goode, Neuder, Pennifill, and Ginn, 1986] describes several conceptual models and solution techniques for estimating potential groundwater contamination due to migration of radionuclides from a burial site.

Volume 4 of this NUREG series [Brenneman and Neuder, in preparation] will provide guidance to reactor licensees for the disposal of very low level radioactive waste pursuant to §20.302. Volume 4 is in preparation and is not available at this time.

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# 2 DISCUSSION

## 2.1 Disposal Pursuant to 10 CFR 20.302

As described earlier, licensees may apply for authorization to dispose of small quantities of radioactive materials in a manner not otherwise authorized in the regulations. The licensee may, for example, seek approval for burials of tritium-contaminated, laboratory-type trash on a quarterly basis or may seek approval for a one-time burial of soil slightly contaminated with carbon-14 from radio-labled plant-uptake studies.

In most cases, proposed disposals pursuant to §20.302 are for burial of low-activity waste in soil. Incineration of radioactive waste at the licensee's facility has been authorized under §20.302 and §20.305 in a few instances. Guidelines for disposal by incineration are established and will therefore not be considered in this document. Several reactor as well as non-reactor licensees have requested authorization for disposal of contaminated waste by means other than incineration or onsite burials [Brenneman and Neuder, in preparation]. In all cases, however, an NRC determination that the radiological risk to public health and safety is negligible does not relieve the licensee of the responsibility for satisfying all other applicable federal, state, and local disposal requirements [Neuder, 1986; Brenneman and Neuder, in preparation].

This document addresses radioactive waste disposal by burial in soil. The pathways, exposure scenarios and assessment methodology described in the next chapter are therefore applicable to near-surface waste burial considerations for any licensee.

## 2.2 Description of Onsite Disposals

Licensees seeking authorization for onsite waste disposal generally propose to bury radioactive waste within the first 20 feet beneath the soil surface. The proposed burial pit varies in size, shape, and depth depending on the types of waste, waste volume, and the licensee's method of excavation. These burial pits are usually filled with waste to within 4 to 6 feet of the original soil surface and the remaining space above the waste is generally backfilled with the excavated soil and mounded above the original surface level.

In most instances, the licensee will propose to use the burial site for infrequent disposals, with consecutive burials usually made in adjacent, noncontiguous areas. Frequency of burials varies from licensee to licensee, ranging anywhere from once each month to once a year. Occasionally, a licensee will request authorization for a one-time release or burial of contaminated material.

Long-term isolation is normally not a consideration in onsite disposal authorizations. In general, an authorization for onsite burial would not be issued if it required controls beyond the time the licensee can reasonably be expected to occupy the site [Neuder, 1986].



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Except for proposed disposals at reactor sites, radioactive wastes are usually packaged in disposal drums prior to burial on site. Surface slumping, depressions, or cave-ins (collectively referred to as subsidence) will frequently occur at onsite disposal areas. Causes of subsidence include infiltration of water into the ground, erosion from surface runoff, void spaces inside and between waste packages, and waste material which degrades in time.

Leaching of radioactive constituents from buried waste will ultimately occur in varying degrees depending on the particular isotopes present in the waste, the amount of water percolating into the disposal unit, the physical condition of the waste package, the physical and chemical forms of the waste, and the contact time between the water and the waste itself.

## 2.3 Generators and Types of Waste

Institutional waste refers to radioactive waste generated at universities, colleges, medical schools, hospitals, testing, and research laboratories. Several institutional waste streams which have relatively high volume but low levels of radioactivity include absorbed liquid scintillation fluids, solidified or absorbed organic and aqueous liquids, biological waste, and trash.

Scintillation fluids are classified as hazardous wastes and would therefore not be acceptable for onsite burials in accordance with Environmental Protection Agency (EPA) regulations [Code of Federal Regulations, Title 40, Part 261]. Biological wastes include animal carcasses (for the most part), plant and animal tissue, animal bedding, excreta, and culture media. Carcass disposals generate large volumes since they are usually packed in absorbent materials, lime, and in double containers. Typical institutional trash consists of paper, plastic, and glass.

The largest volume contributors to institutional wastes are institutions conducting biological research with radioactive materials. Typical volumes vary from 50 $ft^3$ to 5000 $ft^3$. The most common radionuclides associated with bioresearch wastes are H-3, C-14, P-32, S-35, Ca-45, Cr-51, and I-125 of which H-3 is dominant [Beck et al., 1977]. A more complete list of radionuclides associated with institutional wastes, their half-lives and principal radioemissions is given in Table 2.1. Note that most of these radionuclides have half-lives less than 90 days. Radionuclide concentrations in institutional type waste generally do not exceed 0.2 $\mu Ci/cm^3$ (approximately 6 $mCi/ft^3$) in liquid scintillation media and in contaminated trash [Wild et al., 1981].

The predominant radionuclides found in very low level reactor wastes proposed for §20.302 disposals are isotopes of cesium, cobalt, and manganese. Typical volumes vary from 1000 $ft^3$ to 100,000 $ft^3$. In almost all cases, concentrations are in the range 0.1 to 100 pCi/gm.

Generators of industrial waste include producers and distributors of radioactive isotopes, manufacturers of materials and devices containing radioactive isotopes, and users of materials, instruments, and devices containing these isotopes. Certain industrial waste streams generate high volume but relatively low levels of radioactivity, with radionuclide concentration levels generally below a few nanocuries per cubic centimeter [Wild et al., 1981]. Such wastes are generated by industrial laboratories and radiopharmaceutical companies and have characteristics similar to institutional wastes.

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Table 2.1 Principal radionuclides in institutional wastes

| Radionuclide | Half-life | Emission |
|---|---|---|
| H-3 | 12.3y | β |
| C-14 | 5730y | β |
| P-32 | 14.3d | β |
| S-35 | 88d | β |
| Ca-45 | 165d | β |
| Cr-51 | 27.8d | β,γ |
| Fe-59 | 45d | β,γ |
| Co-60 | 5.26y | β,γ |
| Ga-67 | 78.7h | β,γ |
| Se-75 | 120d | β,γ |
| Rb-86 | 18.7d | β,γ |
| Sr-90 | 28.1y | β |
| Mo-99 | 66.7h | β,γ |
| $Tc-99^m$ | 6.05h | β,γ |
| In-111 | 2.82d | β,γ |
| I-125 | 60.0d | β,γ |
| I-131 | 8.05d | β,γ |
| Xe-133 | 5.27d | β,γ |
| Cs-137 | 30.0y | β,γ |
| Yb-169 | 32d | β,γ |
| Tl-201 | 73h | β,γ |

Table 2.2 lists the types of waste proposed for disposal by NRC licensees. Concentrations proposed for disposal in these wastes are typically of the order of .01 $\mu Ci/cm^3$ for non-reactor licensees and 10 $pCi/cm^3$ or less for reactor licensees. Volume of waste, in cubic feet, ranges over four orders of magnitude.

Table 2.2 Types of waste proposed for disposal by NRC licensees pursuant to 10 CFR 20.302

| Reactor Licensees | Institutional/Industrial Licensees |
|---|---|
| Soil | Paper, plastic, glass |
| Sludge | Animal bedding, carcass |
| Sand | Sand, soil, rock |
| Wood | Liquid scintillation media |
| Waste oil | Plant matter |
| | Ash residue |

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## 2.4 NRC Review and Assessment

In accordance with the regulation, licensees must provide information which includes a description of the contaminated material, the disposal conditions, the physical parameters of the site, and the nature of the environment. Volume 1 of this NUREG [Neuder, 1986] provides a comprehensive list of information needed from the licensee when requesting authorization for onsite disposal by burial in soil. The licensee's submittal should include sufficient information to enable the NRC to assess the potential hazard to public health and safety and to determine whether the proposed action will have a significant effect on the human environment.

The submittal is initially reviewed for regulatory conformance, i.e., the request should be appropriate under §20.302. For example, requesting a generic deregulation of a specific waste contaminated with certain small concentrations of short-lived radioisotopes would be inappropriate under §20.302 since generic deregulation requires regulatory rulemaking procedures. An example of an appropriate request under §20.302 would be seeking authorization to dispose of radioactive incinerator ash by burial on the licensee's own property.

The second step in the review of the licensee's submittal is the determination of completeness of information. For disposals by burial in soil, the licensee is expected to provide the information listed in Volume 1 of this NUREG. If the information in the submittal is determined to be complete, the technical assessment based on this information may then be performed.

Volume 1 of this NUREG also provides general guidance to the licensee regarding disposal conditions to be met in order that the proposed disposal be acceptable. For example, the waste proposed for burial should not contain hazardous chemical constituents as defined in the Environmental Protection Agency (EPA) regulation 40 CFR Part 261. Hazardous waste not exempted by statute or rule must be managed in compliance with EPA regulations or the requirements of an approved state regulatory program.

Still other conditions to be followed by the licensee require that the location of the disposal site and its contents should be such as to preclude potential offsite migration or ready access to critical pathways. For example, the waste should be buried well above the water table. Locating the site adjacent to a neighbor's property line or next to animal grazing areas would ordinarily not be acceptable. The NRC reviews the submittal to ensure that these and other conditions described in Volume 1 are met by the licensee.

The next step in the review is to determine whether the proposed quantity of radioactivity fits any of the categories of radionuclides defined in Volume 1 [Neuder, 1986]. Authorization would likely be granted if all requirements and associated disposal conditions described in Volume 1 are met.

Following the preliminary screening of the contents of the submittal, the licensee's radiological impact assessment is reviewed. The assessment generally consists of modeling the radionuclide release to the environment via site-specific critical exposure pathways and the projection of potential radiological dose to an onsite individual and to an offsite member of the public.

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## 2.5 Pathways and Scenarios

For burial of radioactive waste in soil, the critical exposure pathways usually include one or more of the following:

- External exposure to direct radiation from the buried waste.
- Internal exposure from ingestion of agriculture products grown in radioactive soil.
- Internal exposure from inhalation of resuspended radionuclides.
- Internal exposure due to drinking water from a downgradient well contaminated by migrating radionuclides.
- Internal exposure due to drinking water from an onsite well after cessation of disposal activities.

Site-specific parameter values necessary to permit modeling the critical pathways and radiation exposure scenarios are provided by the licensee in accordance with guidance provided in Volume 1. For example, the depth of burial, the spatial array of the waste pits, the cover thickness, and the overall size of the burial site will influence the dose to an inadvertent intruder from direct external radiation. The size of the burial site and the subsurface location of the waste will also determine, to a great extent, the internal dose from crops and animal products derived from the site.

The rate at which the radionuclides enter the environment are also estimated, from information provided by the licensee. The frequency of burials, the physical form of the waste, and the type of container used to package the waste are some of the parameters considered when estimating a release rate to the surrounding medium. The radioactivity released from the waste will also be limited by the amount of precipitation that infiltrates into the ground and comes into contact with the waste. Information on precipitation and the quantity of water percolating down to the waste may be obtained from the water balance information provided by the licensee. Radionuclide migration rates through the soil and in the groundwater strongly depend on the chemistry of the waste and the hydrological and geochemical characteristics of the site and are estimated from site-specific parameters.

Several scenarios are appropriate for assessing onsite disposals by burial in soil. These scenarios have incorporated the critical exposure pathways described above.

External Exposure Scenario - After the burial of waste occurs, an individual (intruder) visits, works, or resides on the disposal site for a number of hours throughout the year. While on the site, the intruder is subjected to whole-body radiation exposure from buried waste or from surface soil contamination. The waste may be located at any depth and have various thickness and cross-sectional extent. These geometric factors will influence the calculated dose rate.

Agriculture Scenario - An individual occupies the site soon after it is filled and uses the disposal site to raise vegetables, fruit, and livestock for meat


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and dairy products. Use of the disposal site for raising livestock may be decoupled from raising fruit and vegetable crops depending on the particular situation. The individual's diet from livestock on the site consist of eggs, milk, beef, pork, and poultry. The individual's diet from raising fruit and vegetable crops consists of root, leafy, and other above-ground vegetables as well as wheat, grain, and fruit. During the growing season, the individual is assumed to derive part or all of a total diet, depending on the size of the site. Production periods for most of the agriculture products are assumed to be 90 days. Area yield rates for food products and annual rates of food consumption (Table 4.1) are used to estimate internal exposure due to food ingestion.

Inhalation Scenario - An individual is assumed to work or reside on the disposal area for a number of hours throughout the year. Soil contamination resulting from an accidental spill during waste disposal operations or from an inadvertent waste exhumation due to agricultural activities is assumed to exist on the surface of the soil. The individual is assumed to be subjected to an inhalation dose from airborne concentrations of radionuclides. Airborne concentrations may be due to ongoing, time dependent processes (resuspension model) or preexist in a relatively static form (mass-loading model). For the resuspension process, the top 1 centimeter of soil is assumed to be available for resuspension. A dilution factor may be applied to the soil concentration to correct for dilution due to excavation activities. Airborne radionuclide concentrations due to resuspension processes will vary depending on the size of the disposal area. Area correction factors may be applied to the dose calculation as described in Chapter 4 of this document.

Irrigation Scenario - An individual is assumed to use a contaminated water supply to irrigate an adjacent field at a rate of 150 liters per square meter per month during a 6-month growing season the site is assumed to be irrigated with contaminated water from an onsite disposal area for 10 years prior to the beginning of the scenario. The individual may then be exposed to external radiation from the contaminated soil, to internal radiation from inhalation of resuspended radionuclides, or to internal radiation from ingestion of food products derived from the irrigated field.

Boundary Well Scenario - Radionuclides are assumed to leach from the disposal area and migrate downward to the aquifer. Uniform groundwater flow is assumed to transport the radionuclides in a horizontal direction toward a potable water well downgradient from the disposal area. The well is assumed to be near the boundary of the licensee's property and is used either for irrigation or for drinking water purposes. An individual is assumed to ingest 2 liters per day from this well for a period of 1 year.

Onsite Well Scenario - The onsite well refers to a potable water well constructed within the waste disposal area itself. The well is assumed to be constructed by an individual after the disposal site is filled and no longer in use.

The radiological impact assessment requires an idealized but realistic description of the physical system under consideration. This description, referred to as a "conceptual model," must include a sufficient number of physical parameters to permit both the mathematical characterization of the system and a simulation of its behavior in space and time. Most of the physical parameter values needed

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to model the system may be derived from the information provided by the licensee. Where information is not readily available or uncertainty exists on the part of the licensee, conservative but realistic estimates of parameter values will then be made based on the limited information provided and on the likely range of parameter values applicable to the specific case.

In general, the conceptual model considers the (1) characteristics of the source term, (2) characteristics of the source medium, (3) transport mechanisms, (4) critical pathways, and (5) exposure scenarios. Each of these five considerations may be quantified, to the extent possible, in terms of site-specific data provided by the licensee.

## 2.6 Radiological Dose Assessment and Recommendations

In general, the committed effective dose equivalent for the critical exposure pathways will determine whether the licensee-proposed disposal will or will not be authorized. Experience has shown that for burial under prescribed conditions along with imposed restrictions as to the proximity of nearby water wells on the licensee's property, conservatively estimated doses to the individual from any of the critical pathways generally do not exceed a few millirem for the radionuclides of concern. As a minimum, prescribed conditions as described in Volume 1 of this NUREG [Neuder, 1986] would generally include: (1) adequate site characteristics for limiting radionuclide migration, (2) burials at least 4 feet beneath the soil surface, (3) burials at least 10 feet above the high point of the water table, (4) restricted access, and (5) an exclusion zone for potable water wells in the vicinity of the disposal area.

In keeping with the principle of ALARA, that is, that radiation exposure and release of radionuclide materials should be maintained as low as reasonably achievable [10 CFR 20.1(c)], dose levels conservatively estimated to be no greater than a few millirem per year to offsite individuals are considered to be acceptable levels without being unduly restrictive on the licensee. It is generally agreed that these levels present a very low risk to public health and safety since they are a small fraction of the dose due to background levels of radiation. These levels do not necessarily apply to cleanup criteria following accidental releases of radioactive material. Nor do they necessarily apply to residual contamination such as may exist at inactive uranium mining and milling facilities. These situations are evaluated on a case-by-case basis where the potential risk from radiation exposure is weighed against the cost and practicality of remedial action.

Recommendations to the licensee by the NRC are generally case specific. For example, quantities of longer-lived radionuclides proposed for burials may have to be limited in order to keep projected doses within acceptable limits. Another recommendation might be to not authorize burial of one of several radioisotopes proposed by the licensee for disposal because of excessive curie content of that one isotope. A frequent recommendation would be to authorize burials with the condition that no drinking water wells exist within a prescribed distance from the burial area. This presumes that the licensee controls the site surrounding the burial area and is capable of providing appropriate surveillance. The NRC does not anticipate that disposals will be authorized which will require a period of long-term care after the site is filled. It is expected, however, that control of the site be maintained for several years after it is filled.



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# 3 THEORETICAL CONSIDERATIONS AND COMPUTATIONAL METHODS

The committed effective radiation dose equivalent resulting from the primary exposure pathways described earlier may be estimated using the computer programs and analytical methods discussed in this chapter. These computational methods and pathways are summarized in Table 3.1.

Table 3.1 Computational methods and associated pathways

| Computational Method and Pathways | Quantity Calculated |
|---|---|
| 1. ONSITE/MAXI1 Code *<br>External pathway<br>Agriculture pathway<br>Airborne pathway | 1. Calculates radiation exposure: (a) external exposure from surface and buried waste (b) internal exposure from ingestion of radioactive food products, (c) internal exposure from inhalation of resuspended radionuclides. |
| 2. MOCMOD84 Code<br>Groundwater pathway | 2. Calculates radionuclide concentration in groundwater. Area source, two-dimensional groundwater flow, and radionuclide transport, dispersion, retardation, and decay. |
| 3. Analytical Method<br>Groundwater pathway | 3. Calculates radionuclide concentration in groundwater. One- and two-dimensional analytical computational forms for radionuclide transport in flowing groundwater-point, line, area sources with instantaneous, exponential and continuous leaching functions. |

* The ONSITE/MAXI1 code is not used in estimating the drinking-water dose via the groundwater pathway unless groundwater concentrations are known and can be directly entered as input data.

## 3.1 The ONSITE/MAXI1 Code

The ONSITE/MAXI1 code [Napier et al., 1984; Kennedy et al., 1986, 1987] contains two primary computer programs, MAXI1 and ONSITE, and an extensive data base. Complete listings of the computer programs and data files can be found in Kennedy et al. [1987]. ONSITE is an interactive program that allows the user to create and use the radiation-exposure scenarios. MAXI1 is then used, with the scenario information, to calculate dose to an individual exposed to radiation from several selected pathways resulting from onsite burial of radioactive wastes. The data base (Section 3.2) contains data files of dose conversion factors for various pathways, master radionuclide and organ metabolic libraries, data, and reference generic environment data.



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The ONSITE/MAXI1 code may be used to model the following pathways:

- Direct external radiation exposure from surface contamination.
- Direct external radiation exposure from subsurface waste.
- Ingestion of crops grown in contaminated soil.
- Ingestion of animal products derived from the contaminated site.
- Ingestion of crops grown in soil irrigated with contaminated water.
- Ingestion of crops contaminated by radionuclide airborne deposition.
- Inhalation of resuspended radionuclides.
- Ingestion of aquatic food products taken from a contaminated stream.
- Ingestion of contaminated drinking water.*
- Direct external radiation exposure from stored waste.

Site-specific information will generally determine which of these pathways are critical pathways. The ONSITE program solicits scenario information from the user, controls parameter modification, selects the appropriate data files from the data base and constructs the input file for MAXI1. The user is thus given the option of selecting pathways and parameters for a "user-defined" scenario. These input files, the radionuclide library, and other appropriate files are then accessed by MAXI1.

For operation on a Vax or Cyber computer, two auxiliary programs, MAXI2 and MAXI3, are described in the ONSITE/MAXI1 documentation [Napier et al., 1984; Kennedy et al., 1986] that allow user modification of the reference environment data base, if desired. Dose conversion factors, created by MAXI2 for the terrestrial food pathway and by MAXI3 for the aquatic pathway, are stored in the data files where they can be accessed during the scenario simulations controlled by MAXI1. The MAXI2 and MAXI3 programs are not required for operations on a personal computer [Kennedy et al., 1987]. In addition, the data files contain external and inhalation dose conversion factors. These factors were calculated using codes external to the ONSITE/MAXI1 code. The external dose conversion factors were calculated using the ISOSHLD code [Engel et al., 1966; Simmons et al., 1967] and are used for both the mainframe and IBM-PC versions of the code. The inhalation dose conversion factors for estimating doses using the ICRP-2 methods and the Task Group Lung Model were calculated using the DACRIN computer program [Houston et al., 1974].

For the external exposure (direct gamma radiation) scenario, MAXI1 uses the dose conversion factors calculated using the ISOSHLD computer program. These

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* Not used for dose assessments via groundwater pathway. The MOCMOD84 code or the analytical methods described in Sections 3.7, 3.8, and 3.9 of this document are used for groundwater pathway analysis.

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factors that relate the radionuclide source strength to the dose rate in tissue 1 meter above a finite "plane" of contamination, 15 cm thick, or above a finite slab of contamination, 1 meter thick. External dose conversion factors are supplied for surface-soil contamination and for buried radioactive waste beneath either a 0.5-meter or 1.0-meter layer of soil. These dose factors are intended to model doses to an individual standing above the contaminated slab for a given period of time.

## 3.2 Data Base for the ONSITE/MAXI1 Computer Program

For the personal computer version of the ONSITE/MAXI1 computer program, the MAXI2 and MAXI3 auxiliary computer programs for calculating dose conversion factors for terrestrial and aquatic foods are not used. Their calculations are done by a modified version of the MAXI1 computer program directly. In addition, the personal computer version of MAXI1 includes the option to consider the International Commission on Radiological Protection ICRP Publication 30 dosimetry methods [ICRP, 1979-1982]. The data base for the personal computer version of the ONSITE/MAXI1 computer program consists of [Kennedy et al., 1987]: (1) the radionuclide master data library, (2) the organ metabolic data library, (3) the food transfer coefficient library, (4) the aquatic bioaccumulation factor library, and (5) the ICRP Publication 30 dose conversion factor library. In addition, external dose factors for various source geometries and inhalation dose factors are included as discussed in Sections 3.3 and 3.5, respectively. The following sections briefly describe the data bases that are used by the personal computer version of the ONSITE/MAXI1 computer program.

### 3.2.1 The Radionuclide Data Library

The Radionuclide Data Library contains all radiological data used by MAXI1. This includes data on radionuclides that are not members of decay chains as well as radionuclides that are members of decay chains, radiological half-lives, and translocation class for soluble and insoluble states of the radionuclide. Translocation refers to the rate at which radionuclides are transported by body fluids from the lungs to the blood and gastrointestinal tract after inhalation.

The Radionuclide Data Library contains 100 radionuclides for consideration in the radiological assessment of onsite waste disposals. These are listed in Table 3.2. These radionuclides are considered most likely to be encountered in institutional, industrial, and reactor low-activity, high-volume wastes - wastes that are potential candidates for onsite burial. Several of these radionuclides are listed with a +D (plus daughters) designation for the International Commission on Radiological Protection ICRP Publication 2 dosimetry calculations [ICRP, 1959]. For these radionuclides, the energies of the short-lived daughters in equilibrium with the parent radionuclides are included in the organ dose and external dose calculations. For other radionuclides and for application of the ICRP Publication 30 dosimetry system, chain decay calculations are performed and daughters are permitted to reach their equilibrium values.

### 3.2.2 Master Organ Data Library

The personal computer version of the ONSITE/MAXI1 computer program [Kennedy et al., 1987] uses a master organ data library for calculating dose to specific organs from ingested radionuclides using the ICRP Publication 2 dosimetry system. This library, designated as ORGLIB, is not needed when the ICRP 30 dose system


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Table 3.2 Radionuclides available for ONSITE/MAXI1 dose assessments

| Radionuclide | Radionuclide | Radionuclide |
|---|---|---|
| $^{3}H$ | $^{144}Ce+D$ | $^{137m}Ba$ |
| $^{14}C$ | $^{152}Eu$ | $^{141}Ce$ |
| $^{22}Na$ | $^{154}Eu$ | $^{151}Sm$ |
| $^{32}P$ | $^{160}Tb$ | $^{235}U$ |
| $^{33}P$ | $^{185}Os$ | $^{231}Th$ |
| $^{35}S$ | $^{191}Os$ | $^{231}Pa$ |
| $^{36}Cl$ | $^{192}Ir$ | $^{227}Ac$ |
| $^{40}K$ | $^{203}Hg$ | $^{227}Th$ |
| $^{45}Ca$ | $^{210}Pb+D$ | $^{223}Fr$ |
| $^{46}Sc$ | $^{226}Ra+D$ | $^{223}Ra$ |
| $^{51}Cr$ | $^{228}Th+D$ | $^{237}Np$ |
| $^{54}Mn$ | $^{230}Th+D$ | $^{233}Pa$ |
| $^{55}Fe$ | $^{232}Th+D$ | $^{233}U$ |
| $^{59}Fe$ | $^{233}U+D$ | $^{229}Th$ |
| $^{57}Co$ | $^{234}U$ | $^{225}Ra$ |
| $^{60}Co$ | $^{235}U+D$ | $^{225}Ac$ |
| $^{59}Ni$ | $^{238}U+D$ | $^{238}U$ |
| $^{63}Ni$ | $^{237}Np+D$ | $^{234}Th$ |
| $^{65}Zn$ | $^{241}Pu+D$ | $^{234m}Pa$ |
| $^{75}Se$ | $^{89}Sr$ | $^{234}Pa$ |
| $^{85}Sr$ | $^{89m}Y$ | $^{242}Pu$ |
| $^{90}Sr+D$(a) | $^{90}Sr$ | $^{238}Np$ |
| $^{93}Mo$ | $^{90}Y$ | $^{238}Pu$ |
| $^{94}Nb$ | $^{99}Mo$ | $^{244}Cm$ |
| $^{106}Ru+D$ | $^{99m}Tc$ | $^{244}Pu$ |
| $^{109}Cd$ | $^{99}Tc$ | $^{240}U$ |
| $^{110m}Ag+D$ | $^{103}Ru$ | $^{240}Pu$ |
| $^{111}In$ | $^{103m}Rh$ | $^{243}Cm$ |
| $^{124}Sb$ | $^{103}Pd$ | $^{243}Pu$ |
| $^{125}Sb+D$ | $^{129}I$ | $^{243}Am$ |
| $^{125}I+D$ | $^{134}Cs$ | $^{239}Np$ |
| $^{131}I+D$ | $^{135}Cs$ | $^{239}Pu$ |
| $^{137}Cs+D$ | $^{137}Cs$ | $^{241}Pu$ |
| | | $^{241}Am$ |

(a) Where +D means plus short-lived daughters in equilibrium for the ICRP Publication 2 dose factors.


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is used. In ORGLIB, data are arranged in blocks by radionuclide and are ordered to be compatible with the master radionuclide order given in the radionuclide data library (see Section 3.2.1). Organ data is included for up to 23 organs of the human body.

### 3.2.3 Food Transfer Coefficient Library

The personal computer version of the ONSITE/MAXI1 computer program uses a master food transfer coefficient library (FTRANSLIB) for relating concentrations of elements in soil to concentrations in farm products produced on that soil. The factors in this library are also used to relate the concentrations in animal feed to concentrations in animal products. The data contained in the library have entries for 63 elements arranged by increasing atomic number in a manner that is compatible with the radionuclide master data library.

### 3.2.4 Aquatic Bioaccumulation Factor Library

The aquatic bioaccumulation library contains the factors used by the personal computer version of the ONSITE/MAXI1 computer program relating the concentration of radionuclides in aquatic biota to the concentration of the radionuclides in the water. Separate factors are listed for fresh and salt water. Also included is a factor for the cleanup of drinking water in water treatment plants. Data are included for 63 elements arranged by increasing atomic number in a manner that is compatible with the radionuclide master data library.

### 3.2.5 Internal Dose Conversion Factors

Internal dose conversion factors for inhalation and ingestion based on ICRP Publication 30 [1979-1982] are contained in a separate data library. The library contains data for the same radionuclides considered in the master data library; however, the listing does not require a +D designation to handle the ingrowth of daughter products. This is because chain decay calculations are performed and daughters are permitted to reach their equilibrium values. The internal dose conversion factors have units of Sv/Bq, and the committed effective dose equivalents reported by the ONSITE/MAXI1 computer program are automatically converted into units of rem.

## 3.3 External Exposure Pathway - the ONSITE/MAXI1

External dose conversion factors (DCFs) for various waste disposal geometries were calculated using the ISOSHLD code [Engel et al., 1966, Simmons et al., 1967]. Waste disposal geometries include a 15-cm layer of surface soil contamination, a 1-meter-thick slab of contamination tangent to and immediately beneath the soil surface, a 1-meter-thick slab with 0.5-meter soil overburden and a 1-meter-thick slab with 1.0-meter soil overburden. Each set of external dose conversion factors contains data for three assumed waste densities. The dose conversion factors relate radionuclide source strength (or concentration) to the dose rate in tissue at a point 1 meter above the soil surface.

### 3.3.1 General Source Geometry

The ISOSHLD code, an auxiliary program to the ONSITE/MAXI1 codes, was used to create data files of dose conversion factors for use by MAXI1. ISOSHLD calculates flux and dose rate at an external point due to gamma photons originating


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at all points within a radioactive volume source. Details about the calculation of flux are given in references by Engel et al. [1965], Simmons et al. [1967], and Taylor [cf Goldstein, 1971]. The region between the volume source and external dose point may contain various layered media such as soil, concrete, water, paper, and air. The geometry used to calculate total flux at the dose point is that of a truncated, circular cone of radioactive waste beneath shielding layers of soil and air. The dose point is shielded by a 5-cm layer of tissue.

### 3.3.2 External Dose Conversion Factor Data Files

Five external dose conversion factor data sets were created for use by MAXI1. These are: (1) PLANSOURC, (2) VOLSOURC, (3) BURIEDHF, (4) BURIED1, and (5) STORED. The first two sets correspond, respectively, to a 15-cm-thick layer and a 100-cm-thick layer of radioactive waste, with upper surfaces tangent to the surface of the soil. The third and fourth sets correspond to a 1-meter-thick subsurface layer of radioactive waste covered by 50 cm and 100 cm of soil, respectively. The fifth data set simulates stored waste as a rectangular slab source, 10.0 meters by 30.0 meters with a waste thickness of 1.0 meter. The dose factors relate the radionuclide source strength to the dose rate in human tissue at a point 1 meter above the surface of the soil. This dose rate corresponds to the dose to an individual standing above the waste and exposed to gamma radiation from the subsurface source. The 15-cm layer is referred to in NUREG/CR-3620 [Napier et al., 1984] as a plane source. Each of the five data sets consists of three files for three assumed waste densities; 1.8, 1.0, and 0.6 g/cm$^3$.

For situations in which the subsurface waste layer is thicker than 1 meter, sensitivity studies have shown that the contribution to the dose rate may be neglected (see Section 3.3.3). Alternatively, using a 1-meter slab to model a subsurface layer of contaminant which is less than 1 meter thick may result in a conservative estimate (overestimation) of dose rate for the higher energy gamma emitters.

The dose conversion factors stored in the data files were calculated for a subtending half-angle of 90 degrees, corresponding to the case of a slab source with infinite cross-sectional area. Most onsite disposal areas are considerably smaller than 1 hectare and would be modeled by using the appropriate area correction factors (see Section 4.3).

### 3.3.3 External Exposure Sensitivity Studies

In the development of the external exposure libraries used by the ONSITE/MAXI1 computer program, certain simplifying assumptions were made. A determination of the sensitivity of the results on these assumptions is next discussed. Two primary assumptions are evaluated in the sensitivity studies:

- The effect of waste form density is determined by comparing the external exposure factors originally calculated for a waste form density of 1.8, with factors calculated for densities of 1.0 and 0.6 g/cm$^3$.

- The effect of the slab-source thickness is determined by comparing the external exposure factors calculated for 1-meter-thick and 3-meter-thick slabs.


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The sensitivity studies are performed using the ISOSHLD computer program [Engel et al., 1966; Simmons et al., 1967] and modified input parameters. A summary of the results generated is shown in Table 3.3 for selected radionuclides based on a constant source strength of 1 Ci/m$^3$ of each radionuclide. These results show that there is a strong dependence on waste form density; that is, for a constant source strength, the less the waste density, the greater the calculated dose rate. However, for each waste density there is little dependence upon slab thickness.

Table 3.3 Sensitivity study results for the external exposure pathway - mrem/hr per Ci/m$^3$ for selected waste form densities and slab thicknesses

| | 1.8 g/cm$^3$ | | 1.0 g/cm$^3$ | | 0.6 g/cm$^3$ | |
|---|---|---|---|---|---|---|
| | Slab Thickness: | | Slab Thickness: | | Slab Thickness: | |
| Radionuclide | 1 m | 3 m | 1 m | 3 m | 1 m | 3 m |
| $^{22}$Na | 514 | 514 | 964 | 966 | 1600 | 1630 |
| $^{51}$Cr | 12 | 12 | 28 | 28 | 470 | 471 |
| $^{54}$Mn | 327 | 327 | 684 | 684 | 1140 | 1150 |
| $^{57}$Co | 21 | 21 | 70 | 70 | 117 | 117 |
| $^{60}$Co | 1003 | 1003 | 1930 | 1930 | 3200 | 3270 |
| $^{90}$Sr+D | 2 | 2 | 6 | 6 | 9 | 9 |
| $^{131}$I | 133 | 133 | 323 | 323 | 539 | 541 |
| $^{134}$Cs | 674 | 674 | 1500 | 1500 | 2470 | 2500 |
| $^{137}$Cs+D | 241 | 241 | 573 | 573 | 935 | 942 |

Based on this result, the operation of the ONSITE/MAXI1 computer program has been designed [Kennedy et al., 1987] to permit the user to select the waste form density when performing external exposure calculations. The possible waste form densities that the user may select are 1.8 g/cm$^3$ (the approximate density of soil), 1.0 g/cm$^3$ (the density of water), and 0.6 g/cm$^3$ (the approximate density of noncompacted trash waste forms). Corrections for slab thickness are not, however, included in the external exposure data libraries.

## 3.4 Ingestion Pathway - the ONSITE/MAXI1

The ONSITE/MAXI1 computer program allows the user to select dose calculations based on the internal dosimetry models described by the International Commission on Radiological Protection (ICRP) in either Publication 2 or 30 [1959; 1979-1982]. The ability to produce ICRP Publication 2-based doses is included so that comparisons with the Regulatory Guide 1.109 methods [U.S. Nuclear Regulatory Commission, 1977] can be obtained. The ICRP Publication 30-based methods are included to be consistent with the newer dosimetry system considered by the NRC. Details concerning the ingestion pathway doses calculated by these methods are found in references by the ICRP [1959; 1979-1982].



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The NRC may adopt the use of the newer ICRP Publication 30 methods for estimating public radiation doses. These methods use a system for radiation protection that is based on limiting the total risk of health effects rather than on a controlling or "critical" organ risk. The dose equivalent, H, at a point in tissue is given by the equation [ICRP, 1977]:

$$H = DQN \tag{3-1}$$

where

H = the dose equivalent at a point in tissue,

D = the absorbed dose,

Q = the quality factor to allow for the effect on the detriment of the microscopic distribution of absorbed energy, and

N = the product of all other modifying factors that might account for the absorbed dose rate and fractionation.

In addition to the basic dose equivalent, the ICRP defined the committed dose equivalent, $H_{50}$, to a given organ or tissue from a single intake of radioactive material. This quantity is the dose equivalent that will be accumulated over 50 years following the intake [ICRP, 1977]:

$$H_{50} = \int_{t_o}^{t_o+50y} \dot{H}(t)\, dt \tag{3-2}$$

where

$H_{50}$ = the committed dose equivalent,

$\dot{H}(t)$ = the relevant dose-equivalent rate, and

$t_o$ = the time of intake.

For stochastic effects, the ICRP recommended a dose limitation based on the principle that the risk to an individual should be equal whether the whole body is irradiated uniformly or whether there is nonuniform irradiation. This condition is met provided that [ICRP, 1977]:

$$\sum_T w_T H_T \leq H_{wb,L} \tag{3-3}$$

where

$w_T$ = a weighting factor representing the proportion of the stochastic risk resulting from tissue (T) to the total risk when the body is irradiated uniformly,

$H_T$ = the annual dose equivalent in tissue (T), and



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$H_{wb,L}$ = the recommended annual dose-equivalent limit for uniform irradiation of the whole body.

For the ICRP Publication 30 dosimetry system, the standard dose that is calculated is this weighted sum of individual tissue (or organ) committed dose equivalents known as the committed effective dose equivalent. This value is estimated by the ONSITE/MAXI1 computer program using the recommendations of the ICRP [1977; 1979-1982].

## 3.5 Inhalation Dose-Conversion Factors - The Task Group Lung Model

The MAXI1 computer program uses dose-conversion factors for inhalation that relate the dose to internal organs resulting from breathing air that contains resuspended radionuclides. These inhalation dose-conversion factors are based on estimates of the distribution and retention of inhaled materials in the lung given by the Task Group on Lung Dynamics Model (TGLM), as developed by the International Commission on Radiological Protection [ICRP, 1966]. The dose-conversion factors include revisions to the metabolic data for plutonium and other actinides [ICRP, 1972]. The TGLM model, with minor additional changes to the values of deposition and clearance for materials in the regions of the lung, has been applied in the calculation of "Annual Limits of Intake by Workers" in ICRP Publication 30 [ICRP, 1979-1982].

The TGLM model takes into account the particle size distribution of the inhaled material and defines three retention classes for materials in the lung. These retention classes are used to account for the chemical form of the inhaled material. The clearance classes are defined as Class D, W, and Y, and relate to clearance half-times of material from the lung of 10 days or less, 10-100 days, and greater than 100 days. In the TGLM model, the respiratory system is divided into three regions including the nasal passages, the trachea and bronchial tree, and the pulmonary parenchyma [ICRP, 1979-1982]. The deposition of inhaled material is described by parameters that represent the fraction of the material deposited in each of the three regions of the lung. Aerosols are assumed to contain a log-normal distribution of particle sizes, thus deposition is related to the activity median aerodynamic diameter (AMAD) of the airborne material. A standard particle size of 1 μm is assumed for estimating the inhalation dose-conversion factors used by the MAXI1 computer program.

The TGLM model assumes that daughter products behave metabolically like the inhaled parent radionuclides. The linked, first-order differential equations that define the clearance of material from the lung are modified to include the radioactive decay constant of the daughter and are shown in ICRP Publication 30 [ICRP 1979-1982]. In a similar way, the ICRP describes how the activities of a chain of parent and daughter radionuclides can be treated by the differential equations.

The ICRP TGLM model, in a version of the DACRIN [Houston et al., 1974] computer program, was used in the calculation of ICRP Publication 2 inhalation dose-conversion factors. These factors can optionally be used by MAXI1 to estimate the inhalation dose resulting from the resuspension of radioactive materials in the surface soils. The system of linear differential equations described by the ICRP in the TGLM model was written in a modified form that would permit easy data entry in the DACRIN computer program. The DACRIN computer program


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was selected for this application because hand calculations had previously been performed to verify the correct operation of the code. This step of code verification is consistent with the quality assurance steps provided for the ONSITE/MAXI1 computer software package [Napier et al., 1984].

### 3.6 Comparison of ICRP 2 and ICRP 26/30 Dose-Conversion Factors

The regulations concerning radiation protection in the United States have been historically developed from the recommendations of the International Commission of Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP). The ICRP issued Publication 2 in 1959. This publication contains specific recommendations on dose-rate limits, permissible body burdens of radionuclides, metabolic data for radionuclides, and maximum permissible concentrations (MPCs) in air and water. New information became available over the next 20 years concerning the effects of radiation, the uptake and retention of radionuclides, and the radioactive decay schemes of parent radionuclides. As a result, the ICRP issued Publication 26 in 1977 and Publication 30 in 1979 to supersede Publication 2.

Because the two dosimetry systems rely on different metabolic data and organ-specific models, it is difficult to describe a comparison of the dose-conversion factors that result for the two systems on a general basis. However, previous efforts have been made to provide a comparison of the inhalation committed dose-equivalent factors calculated by each method [Kennedy and Watson, 1981]. This comparison was done for the critical organ for 67 radionuclides. In the comparison, committed dose-equivalent factors (over 50 years) were obtained from NUREG-0172 [Hoenes and Soldat, 1977] for the ICPR Publication 2 method and directly from ICRP Publication 30, Part I [1979]. For most radionuclides, the critical organ dose-equivalent factors calculated by each method agree within about a factor of 5 of each other. A notable exception was found for the isotopes of uranium where the Publication 30 lung factors are about 20 times higher than the Publication 2 factors. This increase was determined to be partially due to the use of the Task Group on Lung Dynamics Model [ICRP, 1966] and to the use of updated metabolic data.

In addition to estimating doses for critical organs, the ICRP Publications 26/30 dosimetry system also contains a provision for estimating the effective dose equivalent. The effective dose equivalent is defined so that stochastic effects, or those malignant and hereditary diseases for which the probability of occurrence is regarded as a function of dose without threshold, can be determined using a single value for the estimated dose. In determining the effective dose equivalent, a dose to the whole body is determined as the sum over all organs of the product of an organ-specific weighting factor (representing the tissue or organ stochastic risk to the total risk when the whole body is irradiated uniformly) times the committed dose equivalent received by that organ. It should be noted that, for public exposure situations, there are some difficulties in determining the appropriate weighting factors and age-dependent dose-equivalent factors that represent the population exposed.

The ONSITE/MAXI1 [Kennedy et al., 1987] computer software package currently allows the user to select the dosimetry models of the ICRP Publication 2 system, or the ICRP Publication 30 system. Thus, both critical organ and effective whole-body doses can be calculated. For those radionuclides that are controlled


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by internal dose resulting from the inhalation or ingestion pathways in the scenario analysis, the critical organ doses should generally be within about a factor of 5.

## 3.7 Groundwater Pathway Modeling

A rigorous solution to the complex partial differential equations governing groundwater flow and contaminant transport in inhomogeneous saturated porous media would provide a three-dimensional description of radionuclide migration as a function of time at all arbitrary locations throughout the aquifer. In most cases, a rigorous three-dimensional description of contaminant migration is impractical as well as difficult to achieve because of the high degree of detail needed in the site-specific hydrogeologic and geochemical data and the complex techniques generally required in any three-dimensional modeling.

Groundwater pathway analysis may be simplified if certain conservative assumptions can be applied in the modeling or if mathematical simulation can be performed in one or two dimensions. For example, contaminant migration may be assumed to be primarily two-dimensional if the aquifer underlying the site is relatively thin. In this approximation, concentrations in the aquifer are considered to be uniformly distributed along the vertical direction and the mathematical description of flow and transport need only be formulated in two dimensions.

In many situations where the data are not available, one may proceed toward a solution by selecting conservative parameter values and make simplifying, conservative assumptions in the modeling. The solution obtained in this way will overestimate the radionuclide concentrations in the groundwater. Stated another way, where precise information does not exist, the uncertainties may be bounded with conservative assumptions. This strategy may be employed for analyzing proposed disposal activities pursuant to §20.302 since the primary objective of the radiological impact assessment is to estimate the maximum potential dose to an individual member of the general public. For example, if the depth of the underlying aquifer is unknown, a relatively small value for the vertical dimension may be assumed and the mathematical analysis proceeds as in the case of the thin aquifer. This approach will lead to an overestimation of the radionuclide concentration since the assumed thinness of the aquifer will underestimate the diluting volume of water.

As another example, where the source term cannot be determined, one may make a conservative simplifying assumption that the radioactive inventory leaches into the aquifer over a relatively short period of time. The resulting calculation will overestimate the radionuclide concentration at points downgradient from the disposal site. Release rates commonly assumed in the modeling include (1) instantaneous release of the entire inventory to the aquifer, (2) decreasing rate of release over an arbitrary period of time, and (3) constant rate of release over an arbitrary period of time. The rates of radionuclide release into the aquifer or the period of time over which the release occurs should be chosen to provide conservative values (overestimates) of the radionuclide concentrations at points downgradient from the site.

Simplifying assumptions in the modeling are acceptable when used with conservatively chosen parameters based on the fact that they generally lead to a conservative estimate (i.e., overestimate) of the radionuclide concentration at


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receptor points downgradient from the source. The conservative concentration value provides guidance for determining the quantity of radioactivity acceptable for disposal. The advantage of this modeling approach is that it usually reduces the amount of site-specific data required for a more rigorous pathway analysis and it simplifies the computational techniques needed for performing the radiological assessment. Volume 3 of this NUREG discusses this kind of modeling approach for the groundwater pathway in greater detail.

Mathematical techniques for estimating radionuclide concentrations in groundwater include numerical methods and analytical methods. The MOCMOD84 code, described in the next section, is a computer code based on numerical methods for solving the groundwater flow and solute transport equations. Section 3.9 describes the analytical method.

## 3.8 Groundwater Pathway - Numerical Model

The MOCMOD84 computer code [Konikow and Bredehoeft, 1978; Tracy, 1982] numerically simulates two-dimensional steady-state or transient groundwater flow and radionuclide transport in a nonhomogeneous saturated porous medium with complex geometry. For two-dimensional simulation, the conceptual model averages the concentration over the vertical and treats transport through the saturated zone by two-dimensional advection and dispersion. Radionuclide injection into the aquifer may be modeled as a point, line, or area source with either steady or transient injection conditions. Radioactive decay and retardation of contaminant flow caused by radionuclide sorption are factored into the model.

Site-specific hydrogeological data needed as input to the model include porosity, dispersivity, soil solids density, distribution coefficient, and saturated thickness of the aquifer. Other data input requirements include radioactive decay rates, aquifer geometry, location of sources, disposal rates, and locations of recharge and discharge points. As mentioned above, if site-specific data are not well-defined, the licensee may need to make certain simplifying but conservative assumptions in order to perform the computer simulation. For example, the aquifer may be approximated as a thin, homogeneous flow system with constant cross-section. This assumption will generally lead to a conservative prediction of concentration since dispersion and dilution effects will be reduced. Other conservative simplifications may include the selection of low values for the distribution coefficient or for the porosity from the range of values published in the literature for that type of radionuclide-soil system. Choosing low values for these parameters tends to reduce dilution of the contaminant plume. This type of conceptual modeling is discussed in greater detail in Volume 3 of this NUREG [Goode, Neuder, Pennifill, and Ginn, 1986].

For MOCMOD84, with summation convention implied, the expression for two-dimensional areal flow may be written [Konikow and Bredehoeft, 1978; Konikow and Grove, 1977]:

$$\frac{\partial}{\partial x_i}\left(T_{ij}\frac{\partial h}{\partial x_j}\right) = S\frac{\partial h}{\partial t} + W, \quad (i,j = 1,2) \qquad (3\text{-}4)$$

where $T_{ij}$ is the transmissivity tensor, h is the hydraulic head, S is the storage coefficient, and W is the inflow/outflow volume flux per unit area representing fluid sources and sinks.



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Choosing the coordinate axes along the principal axes of the transmissivity tensor ($T_{ij} = 0$, $i \neq j$), and using a rectangular, uniformly spaced, block-centered finite difference grid in which nodes are defined at the center of the rectangular cells, this equation is solved numerically for hydraulic head for each node at discrete time steps.

The average (macroscopic) groundwater flow velocity is related to the head gradient by Darcy's Law. The directional components of the flow velocity may be written as:

$$V_i = - \frac{K_{ij}}{\varepsilon} \frac{\partial h}{\partial x_j} \qquad (3\text{-}5)$$

where $K_{ij}$ is the hydraulic conductivity tensor and $\varepsilon$ is the porosity of the aquifer. After computing the head distribution for a given time step, the flow velocity is computed at each node on the basis of the gradient of the calculated heads.

The equation describing mass transport and dispersion in flowing groundwater may be derived from the principle of mass conservation. For two-dimensional areal flow, assuming time-independent head gradients and saturated thickness, the mass transport and dispersion in a saturated porous medium may be described [Konikow and Bredehoeft, 1978; Konikow and Grove, 1977] by:

$$\frac{\partial C}{\partial t} = \frac{1}{b} \frac{\partial}{\partial x_i} \left( b D_{ij} \frac{\partial C}{\partial x_j} \right) - V_i \frac{\partial C}{\partial x_i} + \frac{(C-C')W}{\varepsilon b} \qquad (3\text{-}6)$$

where C is the concentration of the solute mass (radionuclide concentration), b is the thickness of the saturated medium, $D_{ij}$ is the coefficient of dispersion tensor, $V_i$ is the flow velocity in the i-direction, and C' is the concentration of solute mass in the source or sink. For an isotropic porous medium, the dispersivity may be defined in terms of two constants - longitudinal dispersivity $\alpha_\ell$ and transverse dispersivity $\alpha_t$. Moreover, if one of the cartesian axes (say x axis) is aligned with the direction of net flow velocity then the dispersion coefficient is reduced to just two components:

$$D_{xx} = \alpha_\ell V_x \quad \text{and} \quad D_{yy} = \alpha_t V_x \qquad (3\text{-}7)$$

To account for radioactive decay and the effects of solute sorption in the porous medium, the left-hand term in equation 3-6 is rewritten as $R_d(\partial C/\partial t)$ and an additional term of the form $(-R_d \lambda C)$ is added to the right-hand side [Tracy, 1982], where $\lambda$ is the radioactive decay rate and $R_d$ is the retardation coefficient. The retardation coefficient will generally be a non-linear function of solute concentration [Tracy, 1982]. In all cases considered here, $R_d$ is taken as a constant, namely:


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$$R_d = 1 + \left( \frac{1-\varepsilon}{\varepsilon} \right) \rho K_d \qquad (3\text{-}8)$$

where $K_d$ is the distribution coefficient and $\rho$ is the aquifer solids density. For no adsorption effect, $K_d = 0$ and $R_d = 1$.

From the preceding equations, it is readily seen that any changes in solute concentration will be a function of the dispersion coefficient which in turn is related to the dispersivity of the medium and to the groundwater flow velocity. The determination of flow velocities, in turn, requires simultaneous solution of the flow equation for hydraulic head and the computation of head gradients.

The solution of the transport equation (3-6) provides radionuclide concentrations at discrete points of the finite difference grid after each time step. Volume 3 of this NUREG provides a detailed discussion of the applications of the MOCMOD84 computer code and a sample case study.

## 3.9 Groundwater Pathway - Analytical Model

The differential equation which describes radionuclide migration in non-homogeneous saturated porous media is amenable to exact (analytical) solution if certain simplifying assumptions are made in the modeling. A simplified analysis is acceptable if one is seeking a conservative estimate of radionuclide concentration and demonstrably conservative parameter values are selected.

To demonstrate the procedure, consider an instantaneous release of radioactivity into a large aquifer with constant flow velocity, and negligible recharge in the vicinity of the disposal area. From a mass balance analysis [Codell et al., 1982], the governing equation describing the time varying concentration at an arbitrary point in the aquifer is:

$$R_d \frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i} \left( D_{ij} \frac{\partial C}{\partial x_j} \right) - V_i \frac{\partial C}{\partial x_i} - R_d \lambda C \qquad (3\text{-}9)$$

where the terms containing $R_d$ account for radioactive decay and sorption in the saturated medium (see discussion in the text following equation 3-7). As before, assuming an isotropic porous medium with unidirectional convective transport along the x direction and using equation 3-7, equation 3-9 becomes:

$$R_d \frac{\partial C}{\partial t} = \alpha_\ell V_x \frac{\partial^2 C}{\partial x^2} + \alpha_t V_x \frac{\partial^2 C}{\partial y^2} + \alpha_t V_x \frac{\partial^2 C}{\partial z^2} - V_x \frac{\partial C}{\partial x} - R_d \lambda C \qquad (3\text{-}10)$$

All parameters are as previously defined. At downgradient distances which are large compared with the dimensions of the disposal area, one may treat an areal release into the aquifer as that of a point source in order to conservatively estimate the radionuclide concentration. Assume a point source of unit activity instantaneously released into the aquifer with groundwater velocity V and choose the location of the release to be at the top of the aquifer (as illustrated in Figure 3.1).


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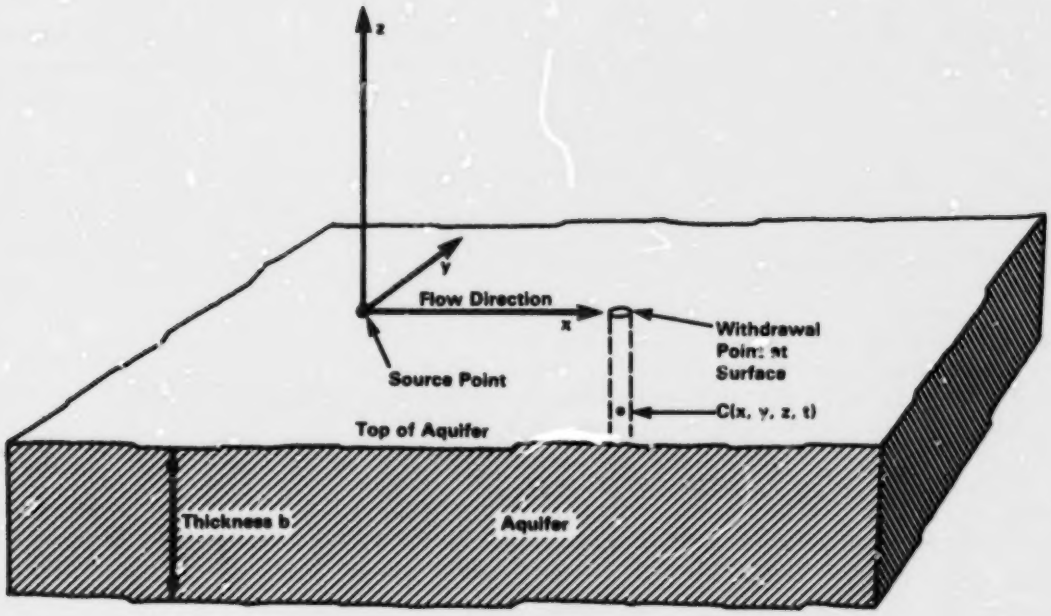


Figure 3.1 Conceptual Groundwater Model

The concentration at a point in the aquifer at a depth z and horizontal distance x from the disposal site is [Codell et al., 1982]:

$$C(x,y,z,t) = \frac{1}{4\varepsilon\pi Vt\sqrt{\alpha_\ell \alpha_t}} \cdot$$

$$\exp\left[-\lambda t - \frac{(x - Vt/R_d)^2}{4\alpha_\ell Vt/R_d} - \frac{y^2}{4\alpha_t Vt/R_d}\right] \cdot$$

$$\left[\frac{1}{b} + \frac{2}{b}\sum_{n=1}^{\infty} \cos\left(\frac{n\pi z}{b}\right) \exp\left[-\frac{n^2\pi^2\alpha_t Vt}{b^2 R_d}\right]\right] \qquad (3\text{-}11)$$



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To simplify the calculations, make the conservative assumption that the aquifer is relatively thin so that at sufficient distances from the source the radionuclides may be considered to be uniformly distributed along the vertical direction. Averaging the concentration along the z direction will make the infinite series term vanish so that the last factor on the right-hand side of equation 3-11 reduces to 1/b. Further, since peak concentrations will occur along the flow centerline and one is seeking a conservative (upper) estimate, a further simplification may be made by setting y = 0. Equation 3-11 becomes:

$$C(x,t) = \frac{1}{4\varepsilon\pi Vtb\sqrt{\alpha_\ell \alpha_t}} \exp\left[-\lambda t - \frac{(x - Vt/R_d)^2}{4\alpha_\ell Vt/R_d}\right] \qquad (3\text{-}12)$$

Equation 3-12 describes the radionuclide concentration C(x,t) in the groundwater at a later time t at an arbitrary distance x from the point of injection. This expression will overestimate the radioactive concentration since it has been derived from a conservative set of assumptions.

The quantity of interest with respect to the licensee's request for disposal authorization is the maximum concentration at some withdrawal point, such as a potable water well, located at the distance x from the disposal location. The peak in the concentration at a distance x will occur at a time t given by:

$$t = \frac{2}{4\lambda + w}\left[\sqrt{1 + \frac{x^2(4\lambda + w)}{4\alpha_\ell^2 w}} - 1\right] \qquad (3\text{-}13)$$

where $w = V/\alpha_\ell R_d$. Substituting this value of t into equation 3-12 will yield an expression for the maximum concentration at the water well located at a distance x downgradient from the source.

If site-specific data on geochemical retardation factors or hydrogeologic parameters such as dispersivity, porosity, and groundwater velocity are not well defined, conservative but realistic values may be selected from a range of possible values, taking into account the type of soil, the radionuclides, the physical and chemical forms of the waste, and other pertinent site-specific characteristics.

A further simplication is possible if the half-life of the radionuclide is sufficiently long (i.e., the decay rate $\lambda$ is sufficiently small) so that $\lambda << w/4$, and if the distance x to the water well is large when compared with the longitudinal dispersivity $\alpha_\ell$ (a likely condition) then equation 3-13 reduces to $t = xR_d/V$. Substituting this expression for t into equation 3-12 gives:

$$C_{mx}(x) = \frac{1}{4\varepsilon\pi bxR_d\sqrt{\alpha_\ell \alpha_t}} \exp\left(-\frac{\lambda x R_d}{V}\right) \qquad (3\text{-}14)$$



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It should be emphasized that equations 3-12 and 3-14 will generally overestimate radionuclide concentrations if site-specific or conservatively-estimated parameter values are employed. However, caution should be exercised when applying generic parameter values to a specific site. In applying equation 3-14, it should be noted that the interval of time over which the concentration peak exists at the withdrawal point is not specified. Since dose criteria (Chapter 4) are based on annual exposures, an appropriately adjusted time-averaged concentration should be considered when calculating the annual dose.

Analytical methods are recommended for use as a preliminary step in the impact assessment process. Should the analytical solution (e.g., equation 3-12 or 3-14) predict concentrations in the groundwater which do not pose a threat to public health and safety, the licensee need not pursue a more complex, computer-assisted analysis for the groundwater pathway. The reader is referred to NUREG/CR-3332 [Till and Meyer, Ch. 4, 1983], NUREG-0868 [Codell et al., 1982] and to Volume 3 of this NUREG for additional groundwater analytical models and their solutions, and for discussions on the selection of conservative parameter values.

## 3.10 Onsite Well

After the site has been filled or no longer used for disposal of waste, an intruder constructs a well within the waste area itself. The individual is assumed to ingest 2 liters of contaminated water per day, throughout the year. To estimate the concentration of radionuclides in the groundwater, the diluting volume is calculated from the annual aquifer flow rate beneath the site and the aquifer cross-section taken to be the aquifer thickness times the width of the waste disposal area. This is a conservative estimate of the volume of water which dilutes the radionuclides to a certain concentration and permits a dose rate determination. The conservative assumption is made that the radioactivity remaining at the time of the final disposal will be relesed to the groundwater in a brief period of time.

In the absence of site-specific data, a very conservative assumption may be made that the volume of water for dilution of contaminants is that quantity representing the annual needs of an individual living in a rural area. This quantity of water is assumed to be the average annual per capita volume withdrawn from a rural domestic well. The average per capita use in the United States is 104 gallons/day [Solley et al., 1983], so that the total dilution volume is the annual quantity of $3.8 \times 10^{-4}$ gallons.

These conceptual models are useful for obtaining very conservative, upper-bound estimates of the radionuclide concentrations in the onsite well.


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# 4 DOSE CALCULATIONS AND ADDITIONAL COMPUTATIONAL CONSIDERATIONS

The basic equation for calculating radiation dose to the individual from any of the radionuclide pathways previously described is [Soldat et al., 1974; Napier et al., 1984; Kennedy et al., 1987]:

$$R_{ipr} = C_{ip} U_p D_{ipr} \quad (4\text{-}1)$$

where

$R_{ipr}$ = dose rate from radionuclide i via pathway p to organ r,

$C_{ip}$ = concentration of radionuclide i in the medium of pathway p,

$U_p$ = usage parameter associated with exposure pathway p, and

$D_{ipr}$ = dose conversion factor for nuclide i, pathway p and organ r.

Concentrations of radionuclides in soil, food, or air must either be prescribed or derived from other considerations. For external exposure due to buried radioactive waste or soil contamination, the radionuclide concentration in the waste or soil is usually determined from measurements or from dividing the curie inventory by the volume of waste or soil. The following sections contain brief discussions of the procedures used for estimating radiation doses from environmental pathways.

## 4.1 Usage Parameters

For ingestion of agricultural products from a contaminated site, the concentration in crops or in animal products is derived from considerations of root transfer from soil, areal deposition onto vegetation, and animal consumption of contaminated forage and feed. Concentrations of radionuclides in irrigated farm produce are derived from concentrations of radionuclides in the irrigation water. Contaminated farm products may result from radioactive contaminants located on the soil surface, root penetration into the radioactive waste, irrigation with contaminated water, or airborne deposition on leafy crops and pastureland.

Table 4.1 contains a listing of the terrestrial and aquatic foods which comprise the entire diet of the intruder. Concentration factors are calculated based on this diet. The modeler's input will define the fraction and type of diet derived from the site. Consideration was given to the radioactive decay time between harvest and consumption of the radionculides (holdup time) when calculating concentration factors for consumed foods.

For ingestion of drinking water from a contaminated well, the concentration in the well downgradient from the site is calculated from a knowledge of the hydrogeologic parameters and modeling the groundwater flow and contaminant transport, as described in the previous chapter.



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Table 4.1 Parameters used for calculation of radiation dose factors from consumption of foods

| Food | Growing Period (days) | Yield ($kg/m^2$) | Holdup (days)[a] | Consumption (kg/year)[b] |
|---|---|---|---|---|
| Leafy vegetables | 90 | 1.5 | 1 | 9.5 |
| Other aboveground vegetables | 60 | 0.70 | 1 | 9.5 |
| Root vegetables | 90 | 9.0 | 1 | 76 |
| Fruit | 90 | 1.7 | 10 | 42 |
| Wheat and grain | 90 | 0.72 | 10 | 51 |
| Eggs | 90 | 0.84[c] | 2 | 19 |
| Milk | 30 | 1.3[c] | 2 | 110[d] |
| Beef | 90 | 0.84[c] | 15 | 39 |
| Pork | 90 | 0.84[c] | 15 | 29 |
| Poultry | 90 | 0.84[c] | 2 | 8.5 |
| Fish | - | - | 1 | 6.9 |

[a] Time between harvest and consumption.

[b] These rates are obtained from Regulatory Guide 1.109 [U.S., NRC, 1977] and prorated by food category using the fraction of total consumed by an average individual as calculated from Napier [Table 8, 1981].

[c] Yield of animal feed (i.e., grain or pasture grass).

[d] Units of liters/year.

For inhalation of airborne constituents, the concentration of resuspended radionuclides is derived from the surface concentration by using a time-dependent resuspension factor or resuspension rate analysis [Anspaugh et al., 1975], or by using a mass-loading approach in the absence of data for the specific site.

The usage parameter, $U_p$, is an exposure rate or an intake rate associated with pathway p. The usage parameter for the external exposure pathway would usually be specified in hours per year. Other units for $U_p$ would be mass per unit time for food ingestion, liters per day for drinking water and volume per unit time for inhalation of airborne contaminants. For example, the occupational exposure rate to a working adult would be 2000 hours per year while the intake rate for drinking water for the average adult would be 2 liters per day. The dose


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rate, R, is generally specified in millirem per year. If R is an annual radiation dose equivalent or a committed radiation dose equivalent, then it would be expressed in millirem. For example, if the soil concentration is in pCi/gm, the exposure rate in hr/yr and the dose conversion factor in mrem/hr per pCi/gm, then the dose rate will be in mrem/hr.

## 4.2 Dose From External Radiation

An individual standing on contaminated soil or above buried waste may be subjected to direct external beta and gamma photon radiation emitted by the radioisotope sources. The equation used for calculating the external exposure dose rate to the organ of reference is:

$$R_r = \sum_{i=1}^{n} C_{ip} U_p D_{ipr} A_{cp} \qquad (4\text{-}2)$$

where $A_{cp}$ is the area correction factor which is used for contaminated areal extents different from 1 hectare (see Section 4.3). The sum is taken over n nuclides and subscript p refers to the external pathway.

The dose conversion factors were tabulated for unit surface-soil contamination and for subsurface or buried contamination. The dose factors were calculated for absorption by 5-cm tissue at 1 meter above the soil surface. Only whole-body dose is calculated. The dose includes exposure to decay gammas and to bremsstrahlung radiation generated in the source medium.

## 4.3 Area Correction Factor for External Exposure

The area correction factor adjusts for the size of the waste burial area, based on fractions of a hectare. The hectare is taken as the size of the reference site, being dose-wise equivalent to the infinite slab source. Sensitivity studies show that the variation of exposure rate with source area is uniform for a wide range of beta-gamma energies, so that a uniform correction across the range of radioisotopes may be applied [Napier et al., 1984]. For all radionuclides of concern, the ratio of exposure rate for small area to exposure rate for large area as a function of fractional hectare of source area is shown in Figure 4.1.

This curve is approximated in the ONSITE computer program as the sum of four linear segments with different slopes. The area correction factors are therefore a function of the fractional hectare (input parameter). Further details may be found in NUREG/CR-3620 and its supplements [Napier et al., 1984; Kennedy et al., 1986, 1987].

## 4.4 Dose From Ingestion of Food Products

Contamination of crops grown on the site may be due to airborne radionuclide deposition on leafy vegetables and on soil, irrigation with contaminated water or root uptake by crops grown in contaminated soil. Concentration of radionuclides in animal products such as meat, eggs, and milk is due to ingestion of contaminated forage, feed, or water by the animal. A full description of the models used for calculating dose from ingestion of food products is given in Kennedy et al. [1987].



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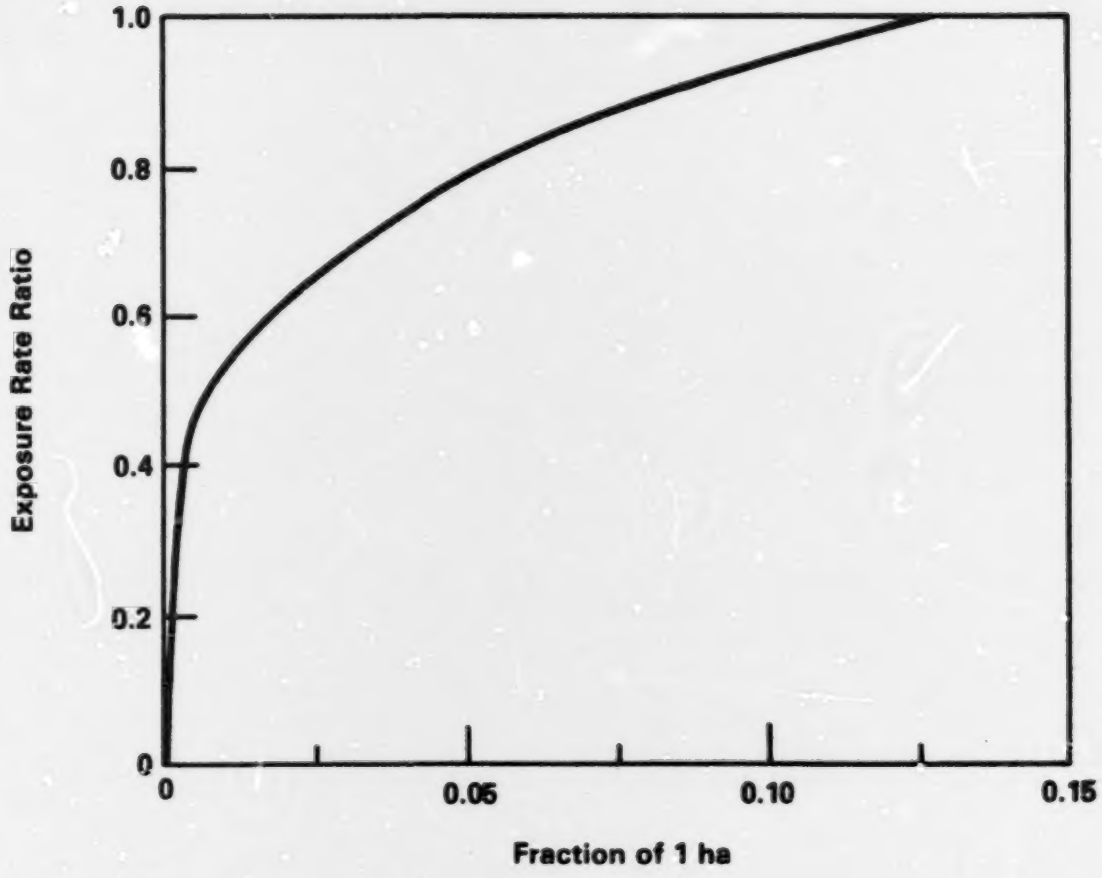


**FIGURE 4.1 Area Correction Factors**

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The deposition rate of airborne particulates may be described by:

$$d_i^a = 8.64 \times 10^4 \, \bar{\chi}_i V_i \qquad (4\text{-}3)$$

where

$d_i^a$ = airborne deposition of radionuclide i, pCi/m$^3$-day,

$\bar{\chi}_i$ = annual average air concentration of radionuclide i, pCi/m$^3$, and

$V_i$ = deposition velocity of radionuclide i, m/sec.

The coefficient $8.64 \times 10^4$ is a unit conversion factor of seconds/day. The deposition velocity is assumed to have the value of $1 \times 10^{-3}$ m/sec for all particulates. This value was chosen to reflect a somewhat greater degree of deposition than usually encountered for finer particulates in elevated stack releases. The average air concentration, $\chi$, may be calculated either by the method of mass-loading or by resuspension analysis (user option).

The deposition rate for radionuclide i from irrigation water is given by:

$$d_i^I = C_{iw} I \qquad (4\text{-}4)$$

where

$d_i^I$ = deposition rate by irrigation, pCi/m$^2$-day,

$C_{iw}$ = radionuclide concentration in irrigation water, pCi/$\ell$, and

$I$ = irrigation rate, $\ell$/m$^2$-day.

Knowing the deposition rates will allow for the determination of the radionuclide concentrations in crops. This concentration is made up of the sum of four terms: (1) deposition on foliage due to resuspension and irrigation, (2) root uptake in contaminated soil due to deposition from resuspension and irrigation, (3) root uptake in waste disposed in the first 15 cm of soil, and (4) root uptake in waste buried below 15 cm. The contribution of each term to the concentration in food products is described in Kennedy et al. [1987].

The sum of the radionuclide concentrations in crops, $C_v$, due to all sources described is given by:

$$C_v = \sum_{k=1}^{4} \sum_{i=1}^{n} C_{iv}^{(k)} \qquad (4\text{-}5)$$

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The radionuclide concentration in animal products such as meat, milk, and eggs due to ingestion of contaminated feed or forage derived from the site is described in Kennedy et al. [1987].

To account for the limited exposure potential from smaller disposal areas, site area correction factors are required in the ONSITE/MAXI1 computer program. Alternatively, the fraction of the total diet grown on the site may be adjusted to account for limited quantities of agricultural products derived from a small disposal area. The user will have the option to adjust intake quantities by specifying either fractional hectare of disposal area or fractional diet (but not both).

## 4.5 Dose From Inhalation

An individual working or residing on the disposal site may be subjected to an inhalation dose from contaminated airborne concentrations of radioactive particulates. Airborne contaminant concentrations may be due to surface-soil contamination resulting from waste disposal operations, from excavation operations or from accidental spills. Air concentrations may be calculated using resuspension analysis [Anspaugh et al., 1975] or the average mass loading of the atmosphere.

The average airborne concentration $\bar{\chi}$ of resuspended contamination, in pCi/m$^3$, is given by:

$$\bar{\chi}(t) = S_f(t)S_A \qquad (4\text{-}6)$$

where

$S_f$ = resuspension factor, m$^{-1}$, and

$S_A$ = surface contamination deposited per unit area, pCi/m$^2$.

The resuspension factor, $S_f$, is defined as the resuspended air concentration per unit surface deposition. The ONSITE/MAXI1 computer program allows the user to select an empirically derived expression for the resuspension factor [Anspaugh, 1975]. Alternatively, the average airborne concentration of resuspended contaminant is the product of the soil concentration, $S_A$, in pCi/gm, and the average mass loading of the atmosphere. In the absence of site-specific data, the mass loading value may be taken as 100 µg/m$^3$ as discussed in Napier et al. [1984]. The user may select either the resuspension model or the mass-loading model when calculating the inhalation dose.

The ONSITE/MAXI1 computer program uses dose conversion factors for inhalation based on either the ICRP Publication 30 or ICRP Publication 2 dosimetry methods. The ICRP Publication 2 inhalation dose conversion factors were calculated using the Task Group Lung Model as contained in the DACRIN [Houston et al., 1974] computer program.

The area correction factor for the inhalation pathway corrects for the decrease in resuspension with decreased site area. The area correction factor for the inhalation pathway is taken to be the same as that for the external exposure pathway [Kennedy et al., 1987], shown in Figure 4.1.


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## 4.6 Dose From Drinking Water

The concentration of radionuclides downgradient from the disposal site may be calculated from the MOCMOD84 computer code or from the analytical solutions as described in Chapter 3. The water ingestion rate is assumed to be 2 liters per day for an individual drinking water from either the boundary well or the onsite well. Fifty-year committed dose equivalents are calculated using internal dose conversion factors tabulated in the literature [Dunning et al., 1981].

If the radionuclide concentration is changing rapidly, either because of radioactive decay or groundwater flow dynamics, care should be taken in specifying the concentration level. An annual average concentration should be calculated before calculating the committed dose equivalent.

The equation used for calculating the 50-year committed dose equivalent to an organ of reference is:

$$(\text{Dose})_r = U_w \sum_{i=1}^{n} C_{iw} D_{ir} \qquad (4\text{-}7)$$

where the subscripts w and i refer to the water pathway and the organ of reference, respectively.

## 4.7 Dose From an Onsite Well

The radionuclide inventory that remains at the time the disposal area is filled or when the land is released for public use is taken as the source of potential radiological dose for the onsite well. The concentration of radioactive contaminants is calculated as described previously. Water ingestion rates are taken as 2 liters per day. Fifty-year dose commitments are calculated using the ingestion dose conversion factors tabulated in the literature [Dunning et al., 1981], and equation 4-7 given previously.

## 4.8 Source Term Considerations

Computational adjustments in the source term should be made before the curie quantity or the radionuclide concentration is specified as an input to the computer programs. In general, the input data for the source term would not be the same as the radionuclide quantity or concentration initially buried by the licensee. This difference is due to radioactive decay prior to reaching the transport medium or to non-uniform spatial distributions at the burial location. These computational adjustments are described below.

### 4.8.1 Temporal Averaging

The ONSITE/MAXI1 computer program calculates dose on an annual basis. Inherent in these calculations is the assumption that the concentration of the radionuclides in the soil is essentially constant over the 1-year time period. That is, while radioactive decay is accounted for by the exponential function in the dose equations, the time step interval in the exponential function is no finer than 1 year. In most cases of waste disposal by burial in soil, the frequency of burials may range from once or twice per month to once or twice per year. Thus, because of radioactive decay, the concentration specified at the time of



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any one burial may be very different from the concentration found at the end of the 1-year period. Adjustments should be made by averaging the concentrations over 1 year before entering the quantity for computation. For each radionuclide in the waste, the concentration C(t) at any time t after disposal is:

$$C(t) = C(o)\ e^{-\lambda t} \qquad (4\text{-}8)$$

where

C(o) = concentration at the time of disposal, and

$\lambda$ = decay constant for that nuclide.

The time average concentration $\bar{c}$, over period T, is obtained from:

$$\bar{c} = \frac{1}{T} \int_o^T C(o)\ e^{-\lambda t}\ dt \qquad (4\text{-}9)$$

For a 1-year period, the time-averaged radionuclide concentration is:

$$\bar{c} = \frac{C(o)}{\lambda}\ [1-e^{-\lambda}] \qquad (4\text{-}10)$$

If the half-life is short, as for example P-32 (half-life 14.3 days), the annual average will clearly be much smaller than the initial concentration. For long-lived radionuclides, equation 4-10 reduces to $\bar{c} = C(o)$ as expected.

The terms "long-lived" and "short-lived" are both relative to the averaging period. Tritium, for example, with half-life 12.3 years is considered long-lived for the purposes of this discussion. Many of the radionuclides found in non-reactor waste streams are short-lived (half-lives less than 1 year) and their concentrations should therefore be time averaged over the 1-year period.

The same averaging considerations apply to the groundwater flow and contaminant transport scenario where analytical solutions are used. When using the MOCMOD code, however, one may account for the sequential injection of radioactive contaminants directly in the user input. That is, the MOCMOD input provides the flexibility for time sequencing injections as well as contaminant injection at different locations. Time averages are therefore not used with the MOCMOD code. In addition, radioactive decay is accounted for by the MOCMOD code itself so that time-averaged corrections for decay need not be done.

### 4.8.2 Spatial Averaging

The input to the ONSITE/MAXI1 program requires the specification of the contaminated area in fractional hectare. The assumption inherent in the MAXI calculations is that the surface contamination area or contamination volume of the waste contains a homogeneous distribution of radionuclides. Specifically, the dose conversion factors in the data files are based on homogeneous distribution of contaminants throughout the surface layer or volume of waste.

After a trench or pit is filled by the licensee's waste disposal operation, a new trench will be excavated in an adjacent area in order to accommodate


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subsequent disposals by the licensee. In general, trenches or pits will not be contiguous but will be separated by areas of undisturbed soil. To model this geometry, it is assumed that the trenches have equally spaced centers, are of equal depth and are separated by uncontaminated areas of soil. Because of this non-uniformity in radionuclide concentration across the disposal site, an average concentration is calculated using:

$$\bar{c}_i = \frac{\sum_{j=1}^{n} c_j A_j}{\sum_{j=1}^{n} A_j} \qquad (4\text{-}11)$$

where

$\bar{c}_i$ = spatially averaged concentration of i-th radionuclide,

$c_j$ = concentration in the j-th disposal region, and

$A_j$ = area of j-th disposal region.

when the disposal region is uncontaminated, $c_j$ is set equal to zero in the calculation.

4.8.3 Container Credit

Waste packaged in strong, tight containers may preclude any radionuclide migration for several years after burial. Corrosion studies have shown, for example, that maximum pitting depths of carbon steel (frequently used waste drum material) at the end of 2 years in various kinds of soil do not exceed 1 or 2 millimeters of material [American Society For Metals, 1978]. Other ferrous metals show similar rates of pitting when buried in soil. Minor changes in composition and structure of steel, for example, are not important to corrosion resistance. Thus, a copper-bearing steel, a low-alloy steel, a mild steel, and wrought iron are found to corrode at approximately the same rate in any given soil. When estimating the source term for dose calculations, credit is given for radioactive decay while still in the waste package.

4.8.4 Storage Credit

Radioactive waste may sometimes be stored for partial decay over a period of several months prior to disposal by burial in soil. In this situation, corrections are made to account for the radioactive decay of the source term before specifying the input data.

4.8.5 Unsaturated (Vadose) Zone Considerations

Radionuclide migration time through the unsaturated zone may result in a substantial reduction in the source term because of radioactive decay. The many uncertainties which exist in attempting to model unsaturated flow allow only a



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rough estimate of the period of time for the nuclides to reach the water table. The MOCMOD84 code simulates groundwater flow and contaminant transport only in the saturated zone so that the data input should reflect the reduced levels of contamination due to radioactive decay during the migration period in the unsaturated zone.

## 4.9 Comparison With 10 CFR Part 61 Methods and Results

An independent derivation of the 10 CFR Part 61 [Code of Federal Regulations, 1986] low-level waste disposal limits was performed using the MAXI1 computer program [Kennedy and Napier, 1984] as a check of the modeling procedure. The derivation used the intruder construction and intruder agriculture scenarios, as defined in the Draft Environmental Impact Statement (DEIS) in support of 10 CFR Part 61 [U.S. NRC, 1981].

The disposal limits shown in 10 CFR Part 61 [1986] are listed for three classes of commercial radioactive wastes: Classes A, B, and C. Class A wastes have minimum stability requirements and low activity levels, and reflect 100 years of radioactive decay that would occur during an institutional control period. Class B wastes permit higher activity levels and must meet more rigorous waste-form requirements to ensure stability after disposal. Class C wastes are required to have a stable waste form and a package with higher integrity than required for Class A or B wastes, and reflect 500 years of radioactive decay. Disposed Class C wastes are further assumed to provide 10 times more protection from intrusion than provided by disposed Class A wastes.

The results of the derivation of the Class A and Class C disposal limits using the MAXI1 computer code, based on maximum annual dose instead of the 50-year dose commitment, are shown in Table 4.2. By carefully following the scenario descriptions given in the DEIS and correctly accounting for radioactive decay, the result generated by MAXI1 generally compare closely to the 10 CFR 61 disposal limits. The notable exceptions to this close agreement are the disposal limits for $^{99}Tc$ and the Class C disposal limit for $^{137}Cs$ where the calculated values are about 10 times the 10 CFR 61 value. The difference in the $^{99}Tc$ concentrations is because a drinking-water scenario, not the intruder scenarios, controlled the 10 CFR 61 value. The $^{137}Cs$ difference for Class C wastes may be the result of radioactive decay calculational differences.

The general agreement of MAXI1 calculated values with the 10 CFR 61 disposal limits, accounting for minor modeling differences, indicates that the results from the two codes compare quite closely.


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Table 4.2 Comparison of calculated and 10 CFR Part 61 low-level waste disposal concentrations

| Radionuclide | 10 CFR Part 61 Concentration ($Ci/m^3$) | | Calculated Concentration ($Ci/m^3$) | |
|---|---|---|---|---|
| | Class A | Class C | Class A | Class C |
| $^{14}C$ | 0.8 | 8 | 0.8 | 8 |
| $^{60}Co$ | 700 | --(a) | 400 | --(a) |
| $^{59}Ni$ | 2.2 | 22 | 1 | 10 |
| $^{63}Ni$ | 3.5 | 700 | 1 | 200 |
| $^{90}Sr+D$(b) | 0.04 | 7000 | 0.03 | 5000 |
| $^{99}Tc$ | 0.3 | 3 | 3 | 30 |
| $^{137}Cs+D$(b) | 1 | 4500 | 0.3 | 30000 |
| $^{239}Pu$ | 10(c) | 100(c) | 30(c) | 300(c) |

(a) Dashes indicate that no Class C limits are established (i.e., the concentration is limited only by practical considerations including the stability of the waste form, internal heat generation, and handling).

(b) +D means plus short-lived daughters.

(c) Units for $^{239}Pu$ are in nCi/g.



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*U.S. GOVERNMENT PRINTING OFFICE:1987-181-682:60004

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NRC FORM 335 (2-84) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

**BIBLIOGRAPHIC DATA SHEET**

SEE INSTRUCTIONS ON THE REVERSE

1. REPORT NUMBER (Assigned by TIDC, add Vol. No., if any)
NUREG-1101
Vol. 2

2. TITLE AND SUBTITLE
Onsite Disposal of Radioactive Waste
Methodology for the Radiological Assessment of Disposal by Subsurface Burial

3. LEAVE BLANK

4. DATE REPORT COMPLETED
MONTH: January YEAR: 1987

5. AUTHOR(S)
S.M. Neuder and W.E. Kennedy, Jr.

6. DATE REPORT ISSUED
MONTH: February YEAR: 1987

7. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Division of Waste Management
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission
Washington, DC 20555

8. PROJECT/TASK/WORK UNIT NUMBER

9. FIN OR GRANT NUMBER

10. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Same as 7. above.

11a. TYPE OF REPORT
Technical

b. PERIOD COVERED (Inclusive dates)

12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)

Volume 1 of this NUREG provides guidance for academic, medical, and industrial licensees seeking authorization to dispose of small quantities of radioactive material by onsite subsurface disposal. Licensee requests for such authorizations are made pursuant to Section 20.302 of 10 CFR Part 20 "Standards for Protection Against Radiation." This volume (volume 2) describes the criteria and technical methodology used by NRC staff to evaluate requests by licensees for approval of onsite disposal by burial in soil. The technical methodology includes the ONSITE/MAXI1 code for calculating radiological exposure from various pathways, the MOMOD84 code, and analytical methods for calculating contaminant transport and concentration of radionuclides in flowing groundwater. Radiological exposure analyses include the following pathways: (1) exposure to direct gamma from any surface contamination or buried waste, (2) drinking water from a well contaminated by migration of radionuclides, (3) ingesting agricultural products derived from radionuclide-contaminated soil, and (4) inhaling radionuclides resuspended at the burial site. Licensee-proposed disposal activities are evaluated in terms of radiological impact on public health and safety and the environment. The estimated committed effective dose equivalent resulting from the technical evaluation will usually be the determining factor in the authorization of the proposed disposal.

14. DOCUMENT ANALYSIS - a. KEYWORDS/DESCRIPTORS
WASTE DISPOSAL
ONSITE BURIAL
RADIOLOGICAL ASSESSMENT
NUCLEAR WASTE DISPOSAL
10 CFR 20.302

b. IDENTIFIERS/OPEN-ENDED TERMS

15. AVAILABILITY STATEMENT
Unlimited

16. SECURITY CLASSIFICATION
(This page) Unclassified
(This report) Unclassified

17. NUMBER OF PAGES

18. PRICE



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